

### Modeling wood properties of planted Loblolly pine from pith to bark and stump to tip

*Richard F. DANIELS*<sup>1</sup>, *Rechun HE*<sup>1</sup>, *Alexander CLARK III*<sup>2</sup>, *Ray A. SOUTER*<sup>3</sup>

<sup>1</sup> Warnell School of Forest Resources, University of Georgia, ATHENS, GA (USA)

<sup>2</sup> USDA Forest Service, Southern Research Station, ATHENS, GA (USA)

<sup>3</sup> Rork Associates, ATHENS, GA (USA)

100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 1040 1041 1042 1043 1044 1045 1046 1047 1048 1049 1050 1051 1052 1053 1054 1055 1056 1057 1058 1059 1060 1061 1062 1063 1064 1065 1066 1067 1068 1069 1070 1071 1072 1073 1074 1075 1076 1077 1078 1079 1080 1081 1082 1083 1084 1085 1086 1087 1088 1089 1090 1091 1092 1093 1094 1095 1096 1097 1

## ABSTRACT

Variation in wood properties follows identifiable patterns within individual trees of Loblolly pine (*Pinus taeda* L.). Wood properties were sampled from disks cut at 1.52 m intervals from 131 mature trees across the natural range of the species. Wood property and mensurational data were used to develop predictive models describing the distribution of key wood properties in three dimensions. Patterns of wood density are described ring-by-ring from the pith to bark and vertically from stump to tip using mathematical models derived from wood sheath increment. A three parameter Logistic function describes the sigmoid curve of latewood specific gravity from pith to bark. By making the Logistic parameters functions of height, a three-dimensional model was developed which describes the changes in latewood specific gravity within the tree. Identifying and predicting properties of the juvenile core and the transition to mature wood are examined. The availability of such models can lead to improved merchandizing decisions for trees and logs and to improved wood quality estimates from forest inventories.

## INTRODUCTION

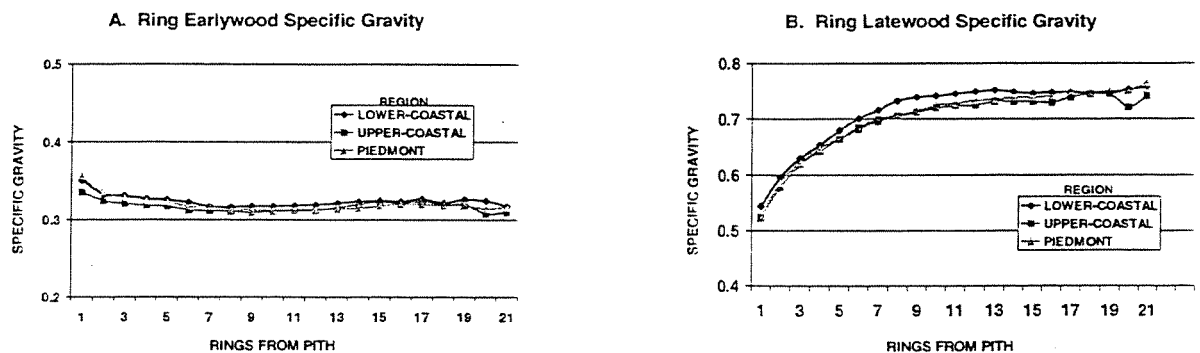
Loblolly pine (*Pinus taeda* L.) is the most important commercial species in the U.S. South. This region produces 58 percent of the marketed timber in the United States and 16 percent of all timber marketed in the world (Wear and Greis, 2002). Loblolly pine is the primary species of the U.S. pulp and paper industry and is also a desired resource for use in the manufacture of lumber and composite wood products. Among the many wood properties important to these manufacturing processes and uses, wood density stands out as the single most important measure due to its high correlation with pulp yield and solid wood strength properties. Specific gravity for Loblolly pine varies with growing conditions, management practices, and genetics (Larson *et al.*, 2001 ; Clark and Daniels, 2003). Wood SG increases significantly with age. Younger trees contain a large proportion of juvenile wood. Juvenile wood differs from mature wood in that it has a lower SG, lower percentage of latewood, and shorter tracheids with larger microfibril angles (MFA : Larson *et al.*, 2001).

Within individual trees, specific gravity and other properties, such as MFA and stiffness, have been observed to vary in predictable patterns from stump to tip and from the pith to the bark (Evans *et al.*, 2000). Quantifying these patterns with mathematical models provides a means to predict wood performance properties within trees and logs, extending and generalizing our knowledge to aid in forest management, wood procurement, and wood utilization decisions. Tasissa and Burkhart (1997) modeled ring specific gravity as a function of physiological age, ring width and latewood proportion using linear models. The same authors (Tasissa and Burkhart, 1998) used linear segmented models to demarcate juvenile-mature wood transition. Phillips (2002) used non-linear functions to model the changes in cross-sectional specific gravity and moisture content of Loblolly pine as a function of height from stump to tip. In each of the modeling examples the authors noted the importance of identifying the tree effect in the model fitting procedure, either by use of mixed-effects models or stochastic parameter estimation.

Models capable of predicting specific gravity and other important properties anywhere within the tree could greatly improve quality predictions and utilization performance. With the ability to predict wood properties such as specific gravity at any point within the stem the Southern pine wood industry could better optimize the merchandising of tree stems for the most appropriate product. In addition, such models would allow growers to forecast the proportion of future stand yields by product class. Such information would contribute to the differentiation of wood markets based on wood quality.

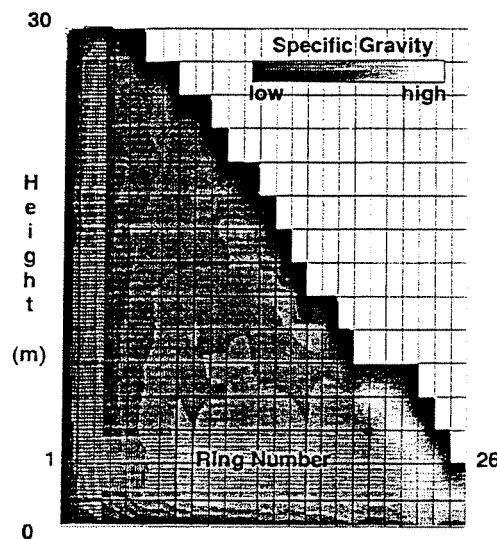
The objective of this research was to develop and demonstrate a three-dimensional model for predicting SG of Loblolly pine by ring, from pith to bark, for any height, from the stump to the tip.

The SG data were assembled in a common dataset and plotted to identify patterns by height and ring (physiological age). Earlywood SG was found to be nearly constant across rings (Fig. 2A). Earlywood SG did not vary by height. Latewood SG followed a typical sigmoid pattern increasing from the pith through a transition period toward an upper asymptote (Fig. 2B). Similar patterns were found at all height levels, with the apparent maximum SG decreasing with height. Because the variability lies in the latewood specific gravity it was decided to model latewood SG as a function of rings from pith and height.



**Figure 2** : Variation in A) earlywood and B) latewood specific gravity at breast height by rings from pith.

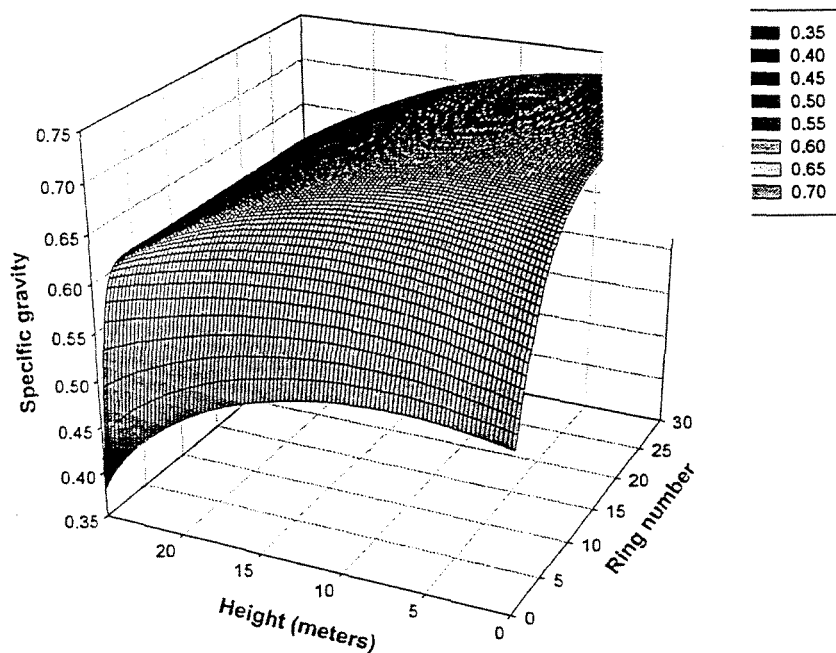
By plotting higher wood densities with lighter shades (Visual Numerics, 2000), Figure 3 depicts the overall variation patterns in latewood SG by ring and by height for all 131 trees. Note that the juvenile core is readily identifiable in the first few rings at all height levels. The transition wood is easily identified after ring 3, leading to denser wood at older physiological ages at all heights. A band of very dense wood is apparent in the lowest several meters.



**Figure 3** : Patterns of radial and longitudinal variation in latewood density for 131 loblolly pine trees.

A three-parameter Logistic model was selected from among several candidate models to describe the sigmoid pattern of variation in latewood SG from pith to bark (Fig. 2A). The three-parameter Logistic function can be written as :

$$f(x) = \frac{\phi_1}{1 + \exp[(\phi_2 - x) / \phi_3]}$$



**Figure 4 :** Three dimensional plot of fitted Logistic equation for Loblolly pine latewood SG as a function of ring number and height.

**Table 2 :** Fit statistics for 3-D Logistic model for Loblolly pine latewood specific gravity.

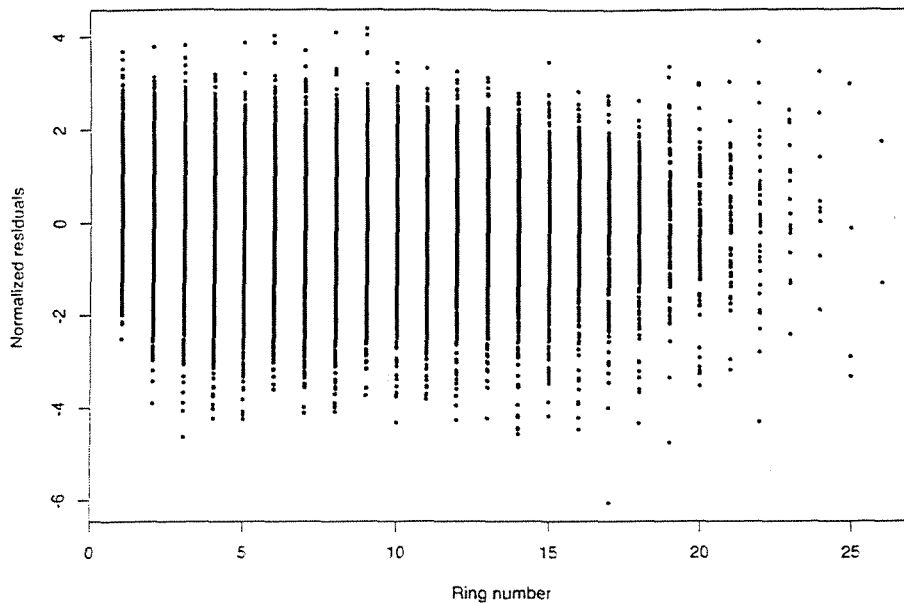
Coefficients	Value	Std Error	t-value	p-value
$b_{01}$	0.7273	0.00285	55.52	<.0001
$b_{11}$	0.0004	0.00021	1.83	0.0665
$b_{21}$	0.0000	0.00000	- 6.51	<.0001
$b_{02}$	-2.8934	0.12794	-22.62	<.0001
$b_{12}$	0.0119	0.00551	2.17	0.0303
$b_{22}$	0.0002	0.00007	3.22	0.0013
$b_{03}$	3.1210	0.09053	34.47	<.0001
$b_{13}$	-0.0299	0.00261	11.47	<.0001

**Standardized Residuals :**

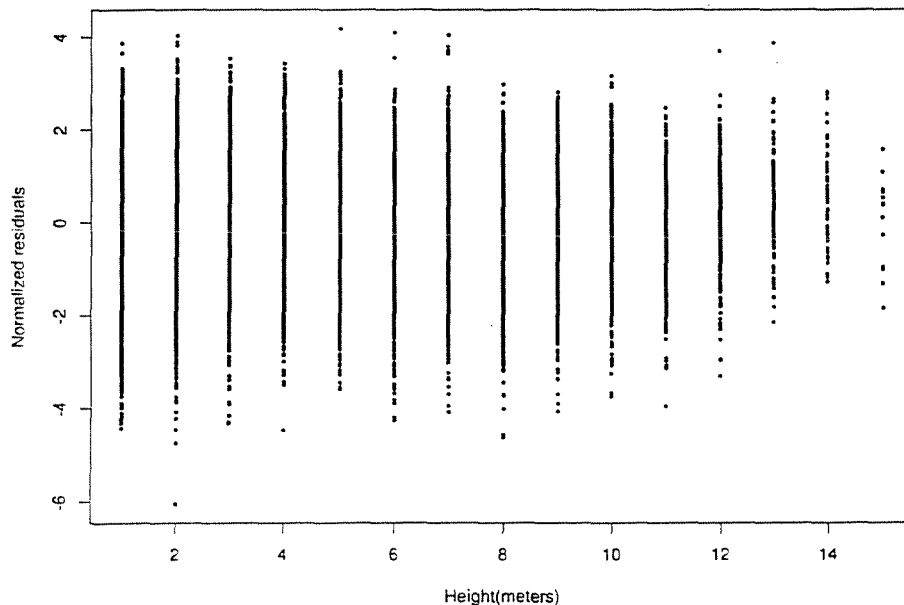
Min	Q1	Med	Q3	Max
-4.3143	-0.64917	0.044971	0.71624	3.6527

**Overall Fit Statistics :**

AIC : -60606    BIC : -60513    Log-Likelihood : 30315  
 Degrees of freedom : 16909 total ; 16901 residual  
 Residual standard error : 0.06215



A



B

**Figure 7 :** Plot of normalized residuals versus A) ring number B) height from fitted 3-D Logistic model for latewood SG of Loblolly pine.

## CONCLUSIONS

By examining variability of specific gravity within loblolly pine trees patterns can be identified by ring, from the pith to the bark, and by height, from the stump to the tip. These patterns follow logical, predictable trends. By identifying the shapes of these trends and choosing appropriate mathematical functions that match these shapes, we identified candidate models for describing specific gravity in three dimensions. The Logistic function was modified to explain a changing sigmoid relationship in three dimensions. This 3-D Logistic model described the major trends in latewood specific gravity, with two exceptions. The function under-predicted a band of dense wood near the bark within the first log and it over-predicted a trend for lower SG at the stump.

Overall these results show promise for a family of wood property models that will improve predictions of wood quality trends within loblolly pine trees and logs. Such models would help in optimizing the merchandizing of wood products. Growers could use these models with growth and yield projections and do a better job of incorporating wood quality considerations into forest management planning and harvest scheduling. At the time of harvest this